A WAVELET-BASED INSTRUMENT FOR DETECTION OF CRACKLES IN PULMONARY SOUNDS

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Abstract-- **Crackles are discontinuous adventitious respiratory sounds, which are considered as signs of various pulmonary disorders, therefore their detection is important in the analysis of lung sounds. In this work, an instrument for separating crackles from stationary lung sounds and quantifying their characteristics is realized with DSP. The detection algorithm is based on increasing transient to background ratio by adaptive filtering and implementing nonlinear operators to wavelet based decomposed lung sounds.**

Keywords- **Wavelets, crackles, pulmonary sounds, detection.**

I.   INTRODUCTION

Stethoscope is a widely used tool for the diagnosis of various disorders in the lungs but is regarded as having low diagnostic value since the interpretation of lung sounds depends strongly on the experience of the physician and therefore tends to be subjective [1]. Application of signal processing techniques to the data obtained through the stethoscope makes the interpretation of lung sounds more objective and the simple and non-invasive auscultation method more valuable in the diagnosis of pulmonary diseases. In recent years, various studies have been conducted to obtain parametric representations of lung sounds to establish a more objective basis for their evaluation [1].

Pulmonary sounds which are roughly classified into breath sounds and adventitious sounds are heard on the chest wall and mouth. Breath sounds which are regarded as normal respiratory noises are synchronous with the flow of air changing from laminar to turbulent through the airways with a frequency spectrum of 200-600 Hz in healthy lungs. Crackles with a duration of less than 70 ms and a frequency spectrum of 100 to 2000 Hz constitute a significant component of adventitious sounds. They are often attributed to the bubbling of secretions in the airways or to the explosive change in gas pressure in small airways. Crackles are basically classified as fine and coarse. Timing (inspiratory, expiratory; early and late), pitch (high or low) and number of crackles (scanty and profuse) in pulmonary sounds reflect to type and stage of disease [1]. For example, in patients with chronic air flow obstruction and bronchiectasis, low pitched crackles, known as coarse crackles, are produced whereas crackles of interstitial fibrosis are high pitched or fine and occur in mid to late inspiration. The waveform of a typical crackle may be seen in Fig. 1.

In spite of their diagnostic value in the evaluation of pulmonary sounds, crackles, due to their short duration, are difficult to detect since the human ear is unable to distinguish events occurring in milliseconds. Moreover, crackles, being localized in time, are not significantly represented in the total spectrum of pulmonary sounds. In this study, a DSP based instrument is implemented for the on-line detection of crackles in pulmonary sounds. The algorithm implemented in the DSP is based on a method developed earlier in our laboratory for the detection of transients in biomedical signals [2]. The detected crackles are further processed for the display of crackles, the phase of occurrence of crackles within the respiration cycle and crackle parameters. Timing of crackles within a respiratory cycle is made possible by the simultaneous recording of air flow with pulmonary sounds. This instrument is aimed to help the physician to extract and record crackles which are difficult to detect through the stethoscope due to their short duration but whose presence is significant in the diagnosis of different lung disorders.
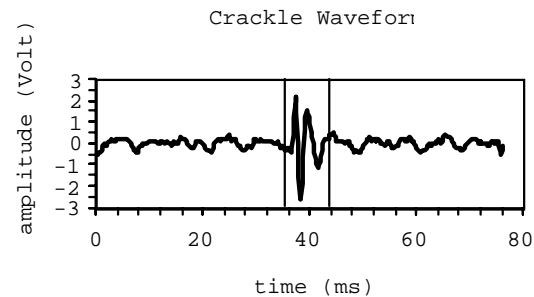

Fig.1 A typical crackle waveform

II.   METHODOLOGY

Lung sounds are recorded via an electret air-coupled microphone transducer placed on the posterior basilar of the chest, are processed with a low-noise preamplifier and a bandpass filter with 60 dB gain and a flat frequency response at 80-2000 Hz [3], and are digitized at 4 kHz, using a 24-bit analog-to-digital converter. The lower cut-off frequency is set at 80 Hz to filter out heart sounds and frictional noise. The flow signal is also recorded by a Fleisch-type flowmeter in order to synchronize on the inspiration-expiration phases and is amplified with a preamplifier with a 40dB gain and a bandwidth between 1.4 Hz to 30 Hz. These signals are scaled to 0-5V voltage range for the input of A/D converter. Motorola DSP56002EVM module is used for digital signal processing. There is a discrete 24-bit codec (A/D and D/A converter) on the module, which is communicating with the DSP via Synchronous Serial Interface (SSI). After transmitting digitized lung sounds and flow signal serially to a digital signal processor (Motorola, DSP56002), a transient detection

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Abstract

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algorithm is applied for separating crackles from stationary lung sounds. The block diagram of the instrument is depicted in Fig. 2.
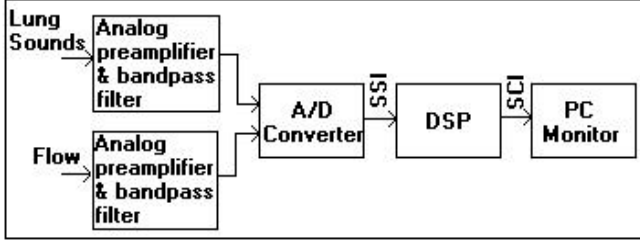

Fig. 2. Block diagram of the instrument.

In the separation algorithm, a prediction error filter (PEF) is first applied to digitized signals for decorrelating the background. This filter is a FIR filter that has adaptively changing coefficients with time as a function of filter inputs (LMS algorithm) [2], [4]. The error signal is next expanded in time scale space, using discrete wavelet transform (DWT). This step is useful for applying non-linear operators to the error signal in different frequency bands [2]. The third step is the application of an inverse discrete wavelet (IDWT) transform to these expanded signals in order to reconstruct the crackles. After the IDWT, an all pole IIR filter, whose parameters are equal to the PEF parameters, is applied for synthesizing the original waveforms of crackles [2]. Finally these crackles are detected by implementing a thresholding and displayed on a PC monitor together with the flow signal. Also displayed on the monitor are the crackle parameters of the detected crackles and their corresponding phases within the respiratory cycle. Fig. 3 shows the block diagram of the detection algorithm implemented with the DSP.
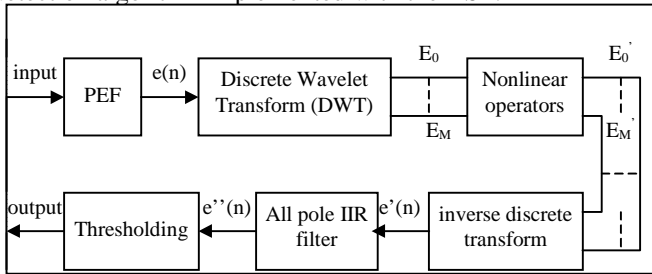

Fig. 3. Block diagram of the implemented algorithm.

Crackle detection algorithm in Fig. 3 was written in DSP assembler and crackles were transferred to a PC via Serial Communication Interface (SCI). DSP56002 is 24-bit floating point DSP, operating up to 40 million instructions per second at 80M Hz, with a single-cycle 24 x 24 bit parallel multiply-accumulator. Each on-chip execution unit (address generation unit, program control unit, two arithmetic logic units), memory and peripheral units operates independently and in parallel with other units through a sophisticated bus system. Due to this parallel operation, an instruction prefetch, a 24 x 24 bit multiplication, a 56 bit addition, two data moves, and two address pointer updates can be executed in a single instruction

cycle. This parallelism allows a four coefficient IIR filter to be executed in only four cycles, the theoretical minimum for single multiplier architecture. At the same time, two serial controllers (SCI and SSI) can send and receive full-duplex data, and a host port can send/receive simplex data. Signal at the output of each block in Fig. 3 was converted to analog using the codec and observed via oscilloscope during the design.

The PEF algorithm supposes that the lung sound (x_n) is a summation of two types of signals: the stationary signal, which can be expressed by an AR model and the nonstationary signal, composed of crackles [2], [4]. A stationary signal or function is deterministic, allowing us to predict its condition at any point in time. From this point of view, if we predict the lung sounds (y_n) with an AR model and if we subtract the predicted signal from the real signal, we find an error (e_n), which mainly consists of the crackles. Equations (1) through (4) show PEF calculations. c_1 and c_2 are adaptively changing coefficients of two-tap FIR filter. And u is the adaptation gain constant, which is very close to 1.

$$y_n = \sum_{k=1}^{2} c_k . x_{n-k} \qquad (1)$$

$$y_n = c_1 . x_{n-1} + c_2 . x_{n-2} \qquad (2)$$

$$e_n = y_n - x_n \qquad (3)$$

$$c_n = c_{n-1} + u . x_{n-1} . e_{n-1} \qquad (4)$$

The error signal at the output of PEF mainly consists of nonstationary components in the lung sounds as well as some stationary components, which could not be suppressed due to adaptation errors. Fig. 4 and Fig. 5 show the error signal at the output of PEF, e(n), for two different inputs: a sinusoidal signal with some nonstationary components and a lung sound signal, respectively. Decrease in stationary to nonstationary ratio (SNR) can be seen easily from these figures.
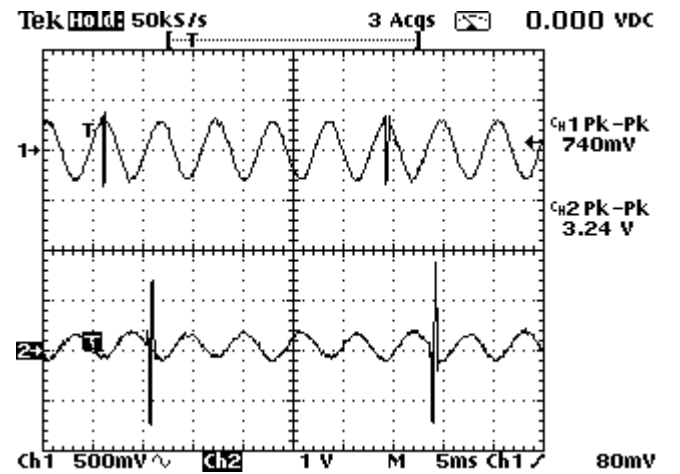

Fig. 4 The output of PEF applied to 200 Hz sinusoidal signal with nonstationary components.
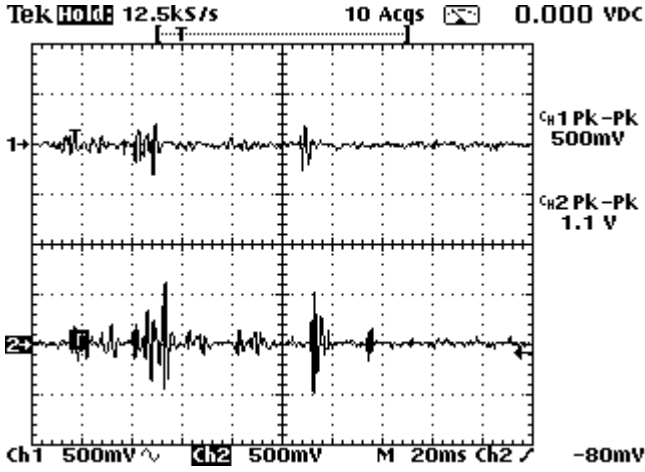
Fig. 5 The output of PEF applied to a lung sound signal.

The error signal at the output of PEF, $e_{(n)}$, is extended in time-frequency space between 0 – 2500 Hz frequency bands, using DWT. Output of DWT consists of six signals corresponding to six different frequency bands, so that the error signal can be analyzed in six different bands. Extending the error signal in different frequency bands is useful for applying nonlinear operators to each band separately. E_0 and E_5 reflect to lowest and highest frequency bands, respectively. DWT is implemented using FIR filters and down-samplers as shown in Fig. 6. Length-six Daubechies filters are selected as FIR filters, due to the strict matching requirement of filter response and crackle characteristics.
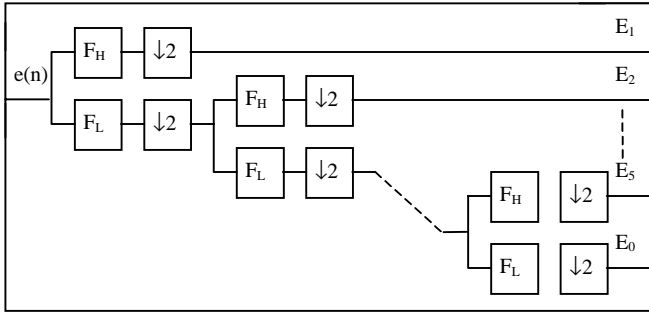

Fig. 6. Discrete Wavelet Transform.

Nonlinear Teager and threshold operators are applied to each band for decreasing SNR. Teager function can be defined as in equation (5). Applying the Teager operator, nonstationary components are amplified while stationary ones are attenuated. After the Teager operator, a threshold operator is applied for zeroing the background. Level of threshold, T, is chosen as the average of last six samples in each band.

$$E'_{(n)} \quad = \quad E(n)^2 - E(n\text{-}1).E(n\text{+}1) \quad (5)$$

$$E''(n) = \begin{cases} E'(n) & , \quad E'(n) > T(n) \\ 0 & , \quad E'(n) < T(n) \end{cases} \quad (6)$$
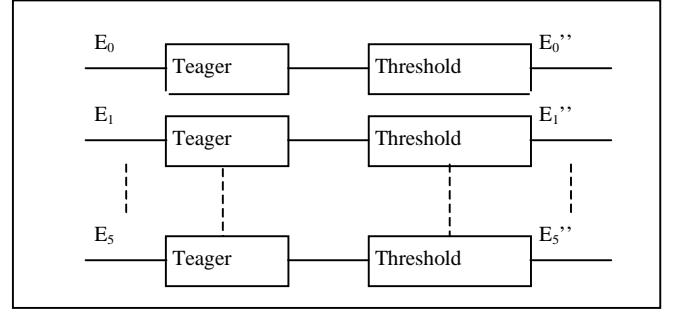
$$T(n) = \frac{\sum_{n=0}^{5} E'(n)}{6} \quad (7)$$

Fig. 7. Nonlinear operators.

After increasing SNR with nonlinear operators, IDWT is applied to construct the error signal back. Implementation of IDWT with FIR filters and up-samplers is shown in Fig. 8. For the protection of symmetry, Daubechies filters are selected as FIR filters again.
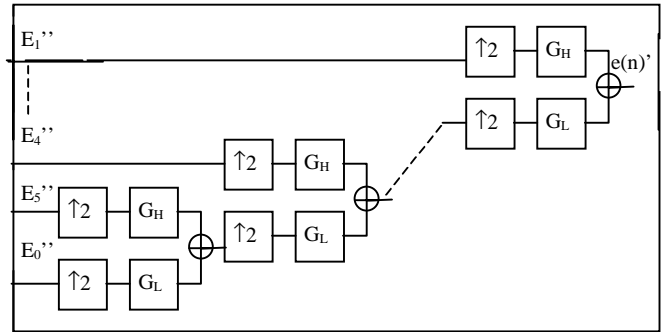

Fig. 8. Inverse Discrete Wavelet Transform.

Fig. 9 shows the signal at the output of IDWT, e'(n), for a lung sound input.
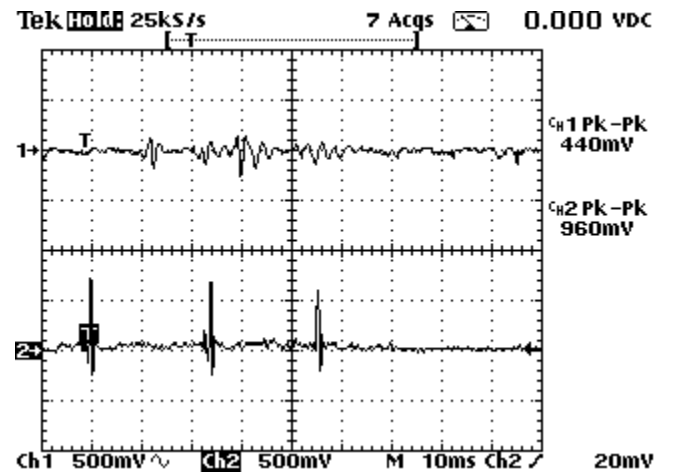

Fig. 9. Crackles at the output of IDWT.

Calculated error signal, e'(n), is passed through an all pole IIR filter, which has the same coefficients with PEF for resembling the crackles to their original shapes maximally. Maintaining the original waveforms of the detected crackles is significant due to the fact that carackle parameters such as the initial deflection width (IDW) and the two-cycle duration (2CD), which depend strongly on the crackle waveform, are calculated and presented as the final step of the detection algorithm. A final thresholding is applied to new error signal, e''(n), for zeroing the background. Thresholding is applied according to the change of amplitudes between consecutive samples. T reflects to thresholding level in (8).

$$output(n) = \begin{cases} e''(n) \,, & e''(n) - e''(n\text{-}1) > T \\ 0 \,, & e''(n) - e''(n\text{-}1) < T \end{cases} \quad (8)$$

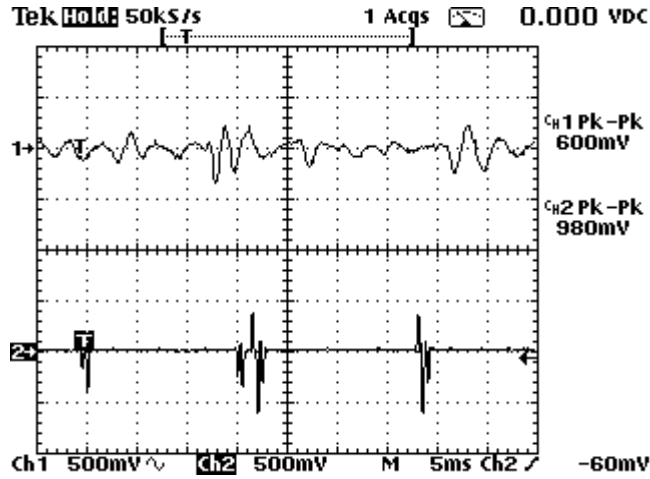Fig. 10 shows the detected crackles at the final output for a sample of recorded lung sound.

Fig. 10. Detected crackles of a lung sound signal sample at the final output.

The detected crackles are further processed for calculation of crackle parameters. The two commonly accepted parameters which characterize and quantify the morphology of crackles are initial deflection width (IDW) and two-cycle duration (2CD). IDW is the duration of the first deflection point of the crackle whereas 2CD is the duration of the first two cycles of the crackle. Crackles with lower duration parameters are classified as fine and those with larger duration parameters as coarse. A third parameter of detected crackle is the phase of occurrence within the respiratory cycle which is divided into six phases, namely as early, mid, late inspiration/expiration.

III.   CONCLUSION

We have built a DSP based instrument for the detection and quantification of cracles in pulmonary sounds. The detection algorithm, which was earlier developed in our laboratory, uses a wavelet approach to separate nonstationary part of the signal. The detected crackles are restored to their original wave shapes for further analysis of their morphology. IDW and 2CD are two parameters which help to classify crackles as fine and coarse. A third parameter of importance in the diagnosis of pulmonary disorders is the time of occurrence of crackles within the respiratory cycle. Crackles along with their parameters are displayed on a PC monitor.

This instrument can be used as an on-line crackle detector to aid the physician to recognize transients of milliseconds duration. Moreover, this instrument may also form part of an expert system designed to diagnose lung disorders based on pulmonary sounds.

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